Substructure in the Coma Cluster: Giants vs Dwarfs

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ABSTRACT

The processes that form and shape galaxy clusters, such as infall, mergers and dynamical relaxation, tend to generate distinguishable differences between the distributions of a cluster's giant and dwarf galaxies. Thus the dynamics of dwarf galaxies in a cluster can provide valuable insights into its dynamical history. With this in mind, we look for differences between the spatial and velocity distributions of giant ($b < 18$) and dwarf ($b > 18$) galaxies in the Coma cluster. Our redshift sample contains new measurements from the 2dF and WYFFOS spectrographs, making it more complete at faint magnitudes than any previously studied sample of Coma galaxies. It includes 745 cluster members – 452 giants and 293 dwarfs. We find that the line-of-sight velocity distribution of the giants is significantly non-Gaussian, but not that for the dwarfs. A battery of statistical

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tests of both the spatial and localised velocity distributions of the galaxies in our sample finds no strong evidence for differences between the giant and dwarf populations. These results rule out the cluster as a whole having moved significantly towards equipartition, and they are consistent with the cluster having formed via mergers between dynamically-relaxed subclusters.

1. Introduction

Galaxy clusters provide us with valuable insights into the formation of large-scale structure in the Universe, as well as being laboratories for studying galaxy formation and evolution. The Coma cluster is the most heavily studied of all galaxy clusters (see Biviano (1998) for an overview). Several lines of evidence, mostly based around the presence of substructure in the cluster, suggest that Coma has recently undergone mergers with smaller clusters. The first evidence for substructure was based on the spatial positions of galaxies on the sky (Fitchett & Webster 1987; Mellier et al. 1988; Escalera et al. 1992; Merritt & Tremblay 1994); more detailed evidence came from maps of the X-ray emitting gas in the cluster obtained by ROSAT (Briel et al. 1992; White et al. 1993; Vikhlinin et al. 1994). Further evidence for a relatively recent merger history in Coma also comes from its anomalously low early-type dwarf-to-giant ratio (Secker & Harris 1996).

A deeper understanding of a cluster's mass distribution and dynamical history can come from the line-of-sight velocities of the cluster members, obtained from redshift measurements. Colless & Dunn (1996, CD96) made the first identification of statistically significant substructure in Coma's velocity distribution (an earlier study by Dressler & Shectman (1988) did not find evidence of significant velocity substructure). CD96 were also able to develop a likely merger history for the cluster, involving three subclusters centred around each of the major cD galaxies: NGC 4874, NGC 4889, and NGC 4839 (strictly, NBC 4889 is a D galaxy since it lacks the extended halo characterising cD galaxies, but we will refer to all three central dominant galaxies as cDs for convenience). Biviano et al. (1996, B96) carried out a similar analysis, although their interpretation of the results was slightly different. Notably, they argued that subclustering is only evident for the brighter (b < 17) galaxies, and that the distribution of fainter dwarf galaxies is much smoother and comprises the "main body" of the cluster.

These studies of the kinematics of Coma have suffered from a lack of statistically large numbers of dwarf galaxy redshifts in their samples. This is important, since the kinematics of the dwarfs may provide some important clues towards the dynamics and formation of the cluster. For example, clusters acquire full dynamical relaxation in two stages. The

first is through violent relaxation, which leaves all galaxies with the same velocity dispersion regardless of mass. The second is through dynamical friction, which acts on longer timescales than violent relaxation, and results in equipartition of energy. This leaves the massive giants with a lower velocity dispersion than the dwarfs, so the evidence of equipartition can be detected by directly comparing the dwarf and giant distributions. The kinematics of the dwarfs might also reveal something about their origins. For example, some subset of the dwarfs may be preferentially accreted at late times from the field (Donas et al. 1995; Bravo-Alfaro et al. 2000; Gallagher et al. 2001), so that rather than being in virial equilibrium they are falling into or through the cluster, either on their first approach (Caldwell et al. 1993, CD96) or having already passed once through the cluster core (Burns et al. 1994; Vollmer et al. 2001). Alternatively, some of dwarfs may in fact belong to satellite populations bound to the cD galaxies in the clusters. In all these cases the kinematics of the dwarfs provide a tell-tale signature. Recent studies that have searched for these signatures in the dwarf populations of clusters other than Coma include Stein et al. (1997) on Centaurus, Drinkwater et al. (2001) on Fornax, and Conselice et al. (2001) and Gallagher et al. (2001) on Virgo.

We have assembled a redshift sample that is more complete at faint magnitudes than any used previously. This was made possible by utilising the ability of the 2dF (2-degree Field – see Lewis et al. 2001) and WYFFOS (Bridges 1998) multi-fibre spectrographs to measure many spectra at once over a wide field of view. This sample is described in section 2. In section 3 we describe how we used this sample to compare the velocity and spatial distributions of giant and dwarf galaxies. We find that the line-of-sight velocity distribution for the giants is non-Gaussian with >99% significance, while the dwarf distribution is close to being a Gaussian. However, a battery of statistical tests failed to detect any other significant evidence for differences between the distributions of giants and dwarfs. In section 4, we show that the lack of detectable differences in the localised velocity distribution rules out the possibility of the entire cluster having proceeded significantly towards equipartition, which is consistent with the estimated timescales for dynamic friction to act in the cluster as a whole. However, we find that the number of available redshifts for dwarf galaxies in Coma is still not enough to distinguish more subtle differences between the giant and dwarf distributions that may have developed in the past due to mergers with smaller clusters.

2. Data

The positions, b magnitudes, and b−r colours of the galaxies in our sample were taken from the GMP catalogue (Godwin et al. 1983). Our redshifts, 1174 in total, comprise the set used by CD96 (a mixture of values taken from the literature and values measured with the

Hydra spectrograph) plus 272 more recently measured redshifts from the 2dF spectrograph at the Anglo Australian Telescope. A further 123 redshifts were taken from the sample measured using the WYFFOS spectrograph on the William Herschel Telescope (Komiyama et al. 2001; Mobasher et al. 2001; Poggianti et al. 2001). 76 of the galaxies observed with WYFFOS were also observed with 2dF, and the corresponding redshifts were averaged; the other 47 were not covered by the 2dF data. Due to these extra redshifts from 2dF and WYFFOS our sample is more complete at faint magnitudes than the sample used by CD96.

Because of the low resolution of available images of the dwarf galaxies in Coma, it was not possible to identify them morphologically. Instead, we distinguish dwarfs from giants using a magnitude cutoff. The choice of a cutoff is arbitrary, as there is no obvious break in the properties of the galaxies in our sample as a function of magnitude. We chose an absolute dividing magnitude of -17, which is consistent with values used in earlier papers — e.g. Poggianti et al. (2001). At the distance of the Coma cluster, this corresponds to an apparent magnitude of $b = 18$ (assuming $H_0 \sim 70$ km s^{-1} Mpc^{-1}). In order to determine the completeness of the giant and dwarf samples, we compare the number of galaxies in the redshift samples with the total number in the GMP catalogue (complete to $b = 20$), excluding those that fall outside the red edge of the cluster colour-magnitude relation, which is described in section 3.3 and Fig. 5. Galaxies bluer than the bottom edge of the colour-magnitude band were left in the sample, since there is a reasonable chance that unusually blue galaxies may be cluster members that have only recently fallen into the cluster. As such, the completeness percentages quoted below are lower limits on the true completeness. The redshift data for the 'giant' sample ($b < 18$) is 80% complete over the whole cluster, and 100% complete within $20'$ of the the cluster centre (which is approximately at the position of NGC 4874). The set of redshifts for galaxies with $b > 18$ is only 34% complete over the whole cluster but 55% complete in the central $20'$. To check for any spatial bias in these dwarf redshifts, we first noted that the limited sample $18 < b < 19$ is about 60% complete over the whole cluster and 85% complete in the central region. Thus any bias present for this limited sample would be small, especially in the central region. We then compared this limited sample with the spatial distribution of galaxies fainter than $b = 19$. We found that redshift measurements for the $b > 19$ galaxies were restricted mainly to the central regions near the cD galaxies. This is an artifact of low completeness away from the centre of the cluster – the $b > 19$ subsample is 39% complete in the central $20'$ but only 22% complete over the central $50'$. Thus there is some bias towards the cluster centre in the dwarf sample. However, all of the statistical tests discussed in this paper were duplicated using the upper-magnitude-limited $18 < b < 19$ dwarf sample, and none of the results differed significantly from those obtained using the $b > 18$ sample (with no upper magnitude limit). We concluded that the spatial bias in the dwarf redshift sample does not significantly affect our results. For the rest

of the paper, the term 'dwarf sample' is assumed to refer to galaxies with b > 18, with no enforced upper magnitude limit.

Galaxies with redshifts in the range $(4000 < cz < 10000)$ km s^{-1} were taken to be members of the cluster – others were assumed to be field galaxies and were excluded. Over the whole cluster, the resulting giant sample contains 452 galaxies and the dwarf sample contains 293 galaxies. In the following we focus mostly on the region within 20′ of the cluster centre, as this was where our redshift sample was most complete. It should be pointed out that the most significant substructure found by CD96 was about 40′ from the cluster centre – the subcluster surrounding NGC 4839, which appears to be in the process of colliding with the rest of the cluster. We devote some attention to this region in the section on spatial substructure below.

3. Results

3.1. Line-of-sight velocity distributions

CD96 found that the line-of-sight velocity distribution for galaxies in Coma was non-Gaussian with a >99% probability. However, their sample contained few dwarfs – it was roughly the same set of galaxies as our sample of giants. To investigate whether this non-Gaussianity is also apparent for the dwarfs, we plot histograms of the velocity distributions of the giants and the dwarfs separately in Fig. 1. At a glance the giant distribution seems to be non-Gaussian, and a Lilliefors test (a Kolmogorov-Smirnov [K-S] test which takes into account the fact that the mean and standard deviation are estimated from the data) confirms this impression, rejecting a Gaussian fit with >99% probability. The dwarf distribution, on the other hand, is only rejected as a Gaussian with less than 75% confidence. Thus, there is strong evidence from the velocities alone for substructure in the giant distribution, but not for the dwarfs.

Despite this hint that the giant and dwarf distributions are different, a direct comparison between the two using a two-sample K-S test gives only a 45% chance that this is actually the case. It may be that there simply are not enough dwarf redshifts to be able to tell whether the dwarf velocities are drawn from the same distribution as the giants or whether they really do in fact follow a Gaussian. To check this, a sample of 293 giants (as many as the number of dwarfs) was selected at random from the giant distribution and tested for Gaussianity. This was repeated 1000 times. We found that 3% of the random samples generated in this way had a <75% chance of being non-Gaussian. Thus there is a small but not negligible possibility that the dwarfs could be drawn from the same distribution as the giants, and

still not show any detectable signs of non-Gaussianity. We had to increase the number of sampled giants to about 330 for there to be a less than 1% chance of a sample having a <75% of being non-Gaussian. Thus we would have to increase the number of dwarf redshifts in our sample before we can tell with any certainty if the line-of-sight velocity distributions really are different.

Given the arbitrary nature of our choice for a dividing magnitude between giants and dwarfs, it is worth investigating whether changing the dividing magnitude affects these results. If b = 17 is used instead of b = 18, the number of giants and dwarfs becomes 306 and 439 respectively – note that there are now more dwarfs than giants. Despite this, the results of the Lilliefors tests and the two-sample K-S test are exactly the same as before – the giants are significantly non-Gaussian but not the dwarfs, while a direct comparison finds only a 45% chance that the two distributions differ. We take this as an indication that our results are not sensitive to small changes in the choice of dividing magnitude. This also increases our confidence that the non-Gaussianity in the line-of-sight velocity distribution really is restricted to the giants, since in this case we can't put the difference down to having less dwarf redshifts than giant redshifts. Finally, since B96 used a cutoff of b = 17 rather than 18 to divide the giants and dwarfs, this result tells us that we can meaningfully compare our results to theirs.

The velocity dispersion for the giants is $\sigma_{Gi} = (979 \pm 30)$ km s^{-1}, and for the dwarfs σ_{Dw} = (1096 ± 45) km s^{-1}. The dwarf dispersion is larger than that of the giants at the 2.2σ level. This is qualitatively consistent with the effects of equipartition, which involves the transfer of kinetic energy from massive galaxies to lighter ones. However, complete equipartition would generate a far bigger difference between the giant and dwarf dispersions. To demonstrate this, we performed a Monte-Carlo simulation in which each galaxy was assigned a velocity drawn from a Gaussian with a dispersion proportional to $1/\sqrt{M}$ (where M is the mass of the galaxy in question), as expected for a cluster in equipartition. The mass of each galaxy is assumed to be proportional to its luminosity, and the mass-to-light ratio is assumed to be the same for all galaxies. After assigning each galaxy a velocity, all of the velocities were scaled so that the dispersion of the total sample (giants plus dwarfs) was the same as that for the real data, about 1000 km s^{-1}. The resulting dispersions for the giants and for the dwarfs (averaged over five simulations) were $\sigma_{Gi} = (482 \pm 16)$ km s^{-1} and $\sigma_{Dw} = (1523 \pm 60)$, a much larger difference than is seen in the real data. We can conclude from this that the cluster as a whole can only have marginally begun to proceed towards equipartition.

There is some evidence that many dwarf ellipticals in clusters arise from the infall of late-type galaxies (Gallagher et al. 2001). The infall scenario predicts that the dwarf velocity distribution should be broader than that of the giants. This is because an infalling population

is not virialised; the kinetic energy is roughly equal to the potential energy, rather than half the potential energy, so the velocities of infalling galaxies should be on average a factor of $\sqrt{2}$ larger than those of a virialised population. As noted above, the dwarf line-of-sight velocity distribution is indeed slightly broader than the giant distribution. However, as well as being wider, we would expect the distribution of an infalling population to be non-Gaussian (because it is not dynamically relaxed), and we see no evidence of that here. The fact that the dwarf distribution is close to Gaussian suggests that even if the dwarfs did form from infall in the past, they have since undergone some form of dynamical relaxation which has erased the kinematic signature of the infall. An alternative explanation is possible if infall occurs in bursts, rather than continuously: a superposition of many 'infall burst' distributions of various dispersions and mean velocities could conceivably (although not necessarily) look Gaussian.

To investigate the cause of the non-Gaussianity of the giants' velocity distribution, the cumulative frequency of giants as a function of cz was plotted along with a cumulative Gaussian with the same mean and dispersion (Fig. 2). We can see that the largest deviation from a Gaussian distribution occurs at $cz \sim 6500$ km s^{-1}. This corresponds to the position of the largest gap in the velocity histogram for the giants (Fig. 1). The gap is not evident in the dwarf distribution. Remarkably, the central velocity of this gap is close to the velocity of NGC 4889 ($cz = 6508$ km s^{-1}). Also, a smaller gap around $cz = 7400$ km s^{-1} seems to correspond to the velocity of NGC 4839. This begs the question of whether or not these gaps are directly caused by the cD galaxies, via mergers or other less obvious dynamical effects. We can gain some insight into this question by looking at the spatial positions of galaxies at different redshifts, as described in the next section.

3.2. Localised Velocity Structure

Fig. 3 is a plot of the smoothed galaxy distribution as a function of projected distance D along the NE-SW axis in the sky and of the line-of-sight velocity cz, for the giants (a) and for the dwarfs (b). D is defined in terms of ΔRA and ΔDec by D = $(\Delta$RA+ΔDec$)/\sqrt{2}$, with NE being positive and D = 0 at the cluster centre. The NE-SW axis is a natural choice because it is the axis on which the three cD galaxies are the most separated, and it seems to correspond roughly to the direction along which the NGC 4839 subcluster is approaching the main body of Coma (CD96). The smoothed density plot in Fig. 3 was generated by convolving the actual galaxy distribution with a 2D Gaussian kernel. The smoothing algorithm was adaptive, meaning that the width of the Gaussian was varied depending on the local density of galaxies. The base values for the dispersions of the Gaussian kernel

were $\sigma_D = 5'$ and $\sigma_{cz} = 200$ km s^{-1}, and these were scaled for each gridpoint by a factor proportional to $1/\sqrt{den}$, where den is the density of galaxies at that gridpoint. Thus the kernel narrows in high-density regions and broadens in low-density regions.

Recall that from the velocity distribution (Figs. 1 and 2) we expect to see gaps in the density of giant galaxies around $cz \sim 6500$ and 7400 km s^{-1}. There are indeed bands of noticeably reduced density at these redshifts, but they are not strongly localised. The only identifiable holes are at $D = \pm\ 20'$. If the velocity gaps were really caused by the cD galaxies, we would expect to see some correlation between the spatial positions of these galaxies and the gaps, but this does not appear to be the case.

When comparing these two plots by eye there seem to be obvious differences between them, such as the peak in the density of giants at ($D \sim 0'$, $cz \sim 8000$ km s^{-1}) which doesn't occur in the dwarf distribution. However, these differences may well just be statistical fluctuations. We used three different tests to calculate the significance of any differences between the giant and dwarf distributions: a 2D χ^2 test, a 2D Kolmogorov-Smirnov (K-S) test, and a Monte-Carlo resampling test. Details concerning the first two can be found in Press et al. (1992). The Monte-Carlo test works by running through all of the galaxies in the sample and reassigning each to either the dwarf group or the giant group at random, where the probability of being a dwarf is just the ratio of the number of dwarfs to total number of galaxies in the real sample. A large number of these reassigned samples (~ 1000) are generated, and for each the binned statistic $Diff$ is calculated. $Diff$ is defined by

$$Diff = \sum_i \left(\frac{D_i}{D_i + G_i} - P \right)^2 \tag{1}$$

where D_i and G_i are the numbers of dwarfs and giants in bin i and $P = D_{tot}/(D_{tot} + G_{tot})$ is the probability that any given galaxy is a dwarf. We then compare the value of $Diff$ for the real sample with the range calculated for the Monte-Carlo reassigned samples to obtain an estimate of the likelihood that the dwarfs and giants are from different distributions. Note that the $Diff$ statistic is very similar to the χ^2 statistic; the difference is that for $Diff$ each term in the sum is not weighted by the total number of galaxies in that bin, so the result is less sensitive to small differences in highly populated bins than would be the case for χ^2.

Each test was applied firstly to all the galaxies with $-50' < D < 50'$ and $5000 < cz < 9000$ km s^{-1} (henceforth referred to as the *large* range), and then again to just the galaxies with $-20' < D < 20'$ and $6000 < cz < 8000$ km s^{-1} (henceforth referred to as the *central* range). When calculating the χ^2 and Monte-Carlo statistics, any bins with less than 5 galaxies total (giants and dwarfs) were neglected. The number of bins was chosen to be the maximum for which the number of neglected bins did not exceed 25% of the total. This turned out to be a 6×6–bin grid for the large range, and a 5×5 grid for the central range.

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The results for each test when applied to the D-vs-cz distribution, quoted as the probability that the giant and dwarf distributions differ, are given in Table 1. In summary, these tests give no better than a $\sim$85% chance that the two distributions are different, which is not enough to make any strong claims that statistically significant differences exist.

Another way to investigate how velocity substructure correlates with spatial position is to plot the galaxy densities on the sky for restricted redshift ranges. We have done this for three different (but slightly overlapping) ranges: $5400 < cz < 6600$ km s^{-1}, $6400 < cz < 7600$ km s^{-1} and $7400 < cz < 8600$ km s^{-1}. The motivation for choosing these three ranges is related to conflicting claims made by CD96 and B96 regarding which velocity structures are associated with which of the cD galaxies. Both papers agree that the peak in galaxy density around (D $\sim 0'$, $cz \sim 7000$ km s^{-1}) is associated with NGC 4874. However, they don't agree about which galaxies are associated with NGC 4889. CD96 identify the galaxies around (D $\sim 5'$, $cz \sim 8000$ km s^{-1}) with NGC 4889, whereas B96 assume the relevant cluster to be that around (D $\sim 5'$, $cz \sim 6000$ km s^{-1}).

The projected density plots for the three velocity ranges (referred to henceforth as A, B and C respectively) for both giants and dwarfs are shown in Fig. 4. The densities for these plots were smoothed using an adaptive Gaussian kernel with base dispersions $\sigma_{\rm RA} = \sigma_{\rm Dec} = 3'$. The densities in each of the three giant plots are set to the same scale - that is, they are all normalised to the maximum value in region B. The same is true independently for the three dwarf plots (in other words, they have the same shading scale as each other but different to the giant plots). ΔRA and ΔDec are restricted to the range $\pm 20'$ to focus attention to the area around NGC 4874 and NGC 4889. In velocity range A, centred around $cz = 6000$ km s^{-1}, both the giants and the dwarfs exhibit density maxima located roughly at the positions of NGC 4874 and 4889, although offset by up to $10'$. In velocity range B, the density maxima near NGC 4889 have vanished, but a peak near NGC 4874 is obvious for both giants and dwarfs (although the peak in dwarf density is slightly less well defined than for the giants). Finally, in velocity range C we still see for the giants a peak halfway between NGC 4874 and NGC 4889, whereas for the dwarfs there is no major peak near either of the two supergiant galaxies. Based on these figures, it is hard to make a clear identification of any one clump in velocity space with NGC 4889. The lack of dwarfs near NGC 4889 in region C seems to point to the galaxies with velocities around $cz \sim 6000$ km s^{-1} (region A) being associated with NGC 4889, consistent with the assumption made by B96, but this is by no means conclusive.

B96 also argue that significant subclustering is only evident for the brighter (giant) galaxies, and not the fainter (dwarf) galaxies. To test this, we used the χ^2, K-S and Monte-Carlo tests to check for statistically significant differences between the spatial distributions

of giants and dwarfs in each of the velocity ranges plotted in Fig. 4. For the χ^2 and Monte-Carlo tests, we used a 4×4 grid of bins, and we neglected any bins containing less than 3 galaxies in total. The results (quoted as the percentage chance of the two distributions being different) are given in Table 2. These results clearly show no evidence of significant differences between the spatial distribution of giants and dwarfs in any of the three redshift ranges. In fact, the distributions of giants and dwarfs seem to be unusually *similar*, compared to what we would expect if each galaxy was assigned to be a giant or a dwarf at random, especially in range B. Based on these results, then, there is no evidence that subclustering is restricted to just the giant galaxies. This is not to say that such a difference does not exist – merely that, if it does, our statistical tests cannot detect it with the number of redshifts available to us. The issue of what differences our tests are in principle capable of detecting is discussed further in section 4.

3.3. Spatial Substructure

The final test we carried out was to compare the spatial distribution of giant and dwarf galaxies, ignoring redshift entirely. The giant and dwarf samples were expanded to include all the galaxies in Coma without determined redshifts. Since redshift can't be used to determine whether these galaxies are part of the cluster or not, we used the colour-magnitude relationship instead. If the b-r colour is plotted against magnitude b for galaxies in the cluster, the points generally fall on a distinct band, as can be seen in Fig. 5a. Galaxies that did not have determined redshifts, and lay outside this band on the colour-magnitude plot (Fig. 5b), were assumed to be field galaxies and were not included in the sample. The resulting expanded giant sample has 529 galaxies, and the expanded dwarf sample has 1041 galaxies.

The smoothed density plots of the spatial distribution of the two expanded samples are shown in Fig. 6. The results look something like the picture of Coma put forward by B96: the distribution of giants shows two distinct peaks around the two central supergiants, NGC 4889 and NGC 4874, while the dwarf distribution has a peak between the two supergiants at a position corresponding to a secondary peak in the ROSAT X-ray map. (There is also another large peak about 10′ W and 5′ S of NGC 4874, which doesn't appear to correspond to the position of any major central dominant galaxy). Once again we applied the three statistical tests to the two distributions to find out whether these apparent differences are significant. Three ranges were tested: a large range (-50′ $< \Delta$RA < 50′, -50′ $< \Delta$Dec < 50′), a smaller central range (-20′ $< \Delta$RA < 20′, -20′ $< \Delta$Dec < 20′), and a range surrounding NGC 4839 where CD96 found the most significant subclustering (-50′ $< \Delta$RA $< $ -10′, -50′ $< \Delta$Dec $<$ -

10′). The two binned tests (the Monte-Carlo and the χ^2) used a 7×7 grid and a cutoff of 10 galaxies per bin for the large region, a 5×5 grid and a cutoff of 8 galaxies per bin for the central region, and a 4×4 grid and cutoff of 5 galaxies per bin for the region around NGC 4839. These values were chosen based on the size of each region and the density of galaxies there. The results of the statistical tests (once again in terms of the percentage chance of difference) are given in Table 3. None of the significance levels produced by any of the tests is high enough to be held up as strong evidence for a statistically significant difference. It could be argued that the grid size used in the binned tests was too large to pick up the features described by B96 (namely the difference in position of the peaks in the giant density and the dwarf density). To check this, we have repeated the tests using twice as many bins in the central region and cutoff of 3 galaxies per bin, and the results are approximately the same as before (no greater than a 90% chance of the two distributions being different). The same is true if we restrict attention to an even smaller central region of (-5′ $< \Delta$RA $< 10'$, -5$< \Delta$Dec $< 10'$) which just encloses the density peaks for both giants and dwarfs.

4. Discussion

B96 concluded that the dwarf distribution was significantly more uniform than the giant distribution. They offered as an explanation the possibility that the original subclusters that make up Coma had time to proceed towards equipartition before they merged, spreading out the dwarfs in both position and velocity space. Our results for the line-of-sight velocity distributions of the giants and dwarfs are consistent with the findings of B96, in that there is significant substructure (and thus non-Gaussianity) present in the giant distribution but not the dwarf distribution. However, we find no evidence for differences between the localised velocity distributions or the spatial distributions of the giants and dwarfs, which contradicts B96. The primary reason why our conclusions differ is that B96 made no direct statistical comparisons between the giant and dwarf distributions. Although to the eye there do appear to be differences, our tests show that there is still a significant probability of the giants and dwarfs belonging to the same distribution. Nonetheless, it is worth investigating whether it is plausible that the original subclusters could have been in equipartition, as B96 proposed.

The main processes by which energy can be transferred from massive galaxies to lighter ones in clusters are two-body relaxation and dynamical friction. The typical timescale for two-body relaxation in a cluster the size of Coma is $t_{tb} \gtrsim 3 \times 10^{11}$ yr (Sarazin 1986), much greater than a Hubble time, so we can expect that dynamical friction will be the dominant process driving the cluster towards equipartition. If we assume that the core of the cluster is an isothermal sphere, the timescale t_{fr} for dynamical friction to significantly alter the

momentum of a galaxy with mass M is given by (Binney & Tremaine 1987):

$$t_{fr} = \frac{66 \text{ Gyrs}}{\ln \Lambda} \left(\frac{r_i}{0.5 \text{ Mpc}}\right)^2 \left(\frac{\sigma}{1000 \text{ km s}^{-1}}\right) \left(\frac{10^{12} \text{ M}_\odot}{\text{M}}\right) \qquad (2)$$

where Λ is the ratio of the largest possible impact parameter to the smallest, r_i is the initial radius of the galaxy's orbit, and σ is the velocity dispersion of the cluster. Typically $\ln \Lambda \sim 3$ (Sarazin 1986); for Coma, $r_i \simeq 0.5$ Mpc, and $\sigma \simeq 1000$ km s^{-1}. When these values are substituted in to Eq. 2, we find that $t_{fr} \simeq 22$ Gyr for a galaxy of 10^{12} M$_\odot$ (a typical mass for a 'giant' galaxy). A galaxy would have to be more massive than 2.2×10^{13} M$_\odot$ to have a dynamic friction timescale less than 1 Gyr. According to Vikhlinin et al. (1994), the masses of the two largest galaxies in the cluster, NGC 4874 and NGC 4889, are both approximately 1×10^{13} M$_\odot$, so not even they should have had time to settle into the centre of the cluster potential. This is consistent with the observation that the galaxy velocities do not show the signature of equipartition, and that the velocities of the main cD galaxies are displaced from the mean velocity of the surrounding galaxies.

Is it plausible that the subclusters conjectured to be merging with Coma would have had time to approach equipartition? A rough criterion for judging this is to require t_{fr} to be less than 1 Gyr for at least the most massive galaxies in a subcluster. The velocity dispersion of a cluster scales roughly as the square-root of its mass, so a subcluster with around 0.1 times the mass of Coma should have a velocity dispersion of $\sqrt{0.1} \times$ the dispersion of Coma, or about 300 km s^{-1}. Then r_i for such a subcluster only needs to be a factor of 3 smaller than that of Coma to to bring t_{fr} below 1 Gyr for a 10^{12} M$_\odot$ galaxy. These values of σ and r_i are well within the range that have actually been observed in small clusters (Adami et al. 1998), so there is a good chance that any subclusters that have merged with Coma would have been at least partially in equipartition.

The next question in this: if Coma is really composed of subclusters that are (or were) in equipartition, are our statistical tests capable of detecting it? We checked this by carrying out some Monte-Carlo simulations. The first set, described above in the section 3.1, reassigned velocities to each of the galaxies in a way consistent with the *entire cluster* being in equipartition. The positions of the galaxies were left unchanged. The resulting velocity distributions showed a marked difference between giants and dwarfs, much larger than the difference seen in the real data. We also tested the D-vs-cz distributions from the simulated data, in exactly the same way as was done for the real data. The result (for the large range) was always a >99.9% probability of the giant and dwarf distributions being different (the results in the central range were a bit less consistent, with $\sim 1/2$ of the simulations resulting in a >99% significance level). So we can be fairly confident that if the entire cluster was in equipartition we would be able to detect it. The fact that we don't is consistent with our

expectation that Coma as a whole is too large to have approached equipartition.

The second set of simulations were done to mimic two equipartitioned sub-clusters (centred around NGC 4889 and NGC 4839 respectively) in the process of merging with a 'main cluster body' centred on NGC 4874. This is approximately the merger scenario proposed by CD96. A certain fraction of the galaxies within 25′ of NGC 4889 and NGC 4839 were randomly assigned as being 'bound'; the fraction was chosen so that the number of galaxies bound to each of NGC 4889 and NGC 4839 comprised 10% of the total cluster population. The galaxies of these two bound populations were assigned velocities consistent with equipartition, with a dispersion scaled to 300 km s^{-1} and a mean velocity equal to that of the relevant cD galaxy. We use 300 km s^{-1} for the dispersion of the bound groups because these groups have about 10% of the mass of the entire cluster, and we expect the dispersion to scale as the square root of the mass; $\sqrt{0.1} \simeq 0.32$, so the bound group dispersion should be roughly one-third that of the entire cluster. The remaining 80% of the cluster population was assumed *not* to be in equipartition (due to the combined effects of earlier mergers, violent relaxation and infall); these galaxies were assigned velocities taken at random from a single Gaussian with a dispersion of 1000 km s^{-1} and a mean equal to the velocity of NGC 4874.

One thousand of these 'merger' velocity distributions were simulated. For each, the line-of-sight velocity distributions for giants and dwarfs had very similar dispersions ($\sim$ 1000 km s^{-1}), just like in the real data. Direct comparisons between the giant and dwarf velocity distributions using a K-S test failed to turn up a significant difference. Remarkably, though, for 37% of the simulated distributions the velocities of the giants were non-Gaussian with a >99% certainty. Conversely, only 1.4% of the dwarf distributions were significantly non-Gaussian. The reason for this is that the effect of equipartition in the bound groups is to reduce the dispersion of giant velocities and spread out the dwarf velocities, so there tend to be distinct peaks in the giant line-of-sight velocity distribution around the velocities of NGC 4889 and NGC 4839 but not in the dwarf distribution. Thus it is plausible that this sort of merger scenario could account for the non-Gaussianity of the real giant distribution and the contrasting Gaussianity of the real dwarf distribution.

The D-vs-cz distributions of the simulated data were also compared, using the 2D K-S two-sample test. The giant and dwarf distributions were found to have on average an 85% chance of being different; only 2.3% of the simulated distributions were found to have a >99% chance of being different. Thus the statistical tests fail to detect the signature of equipartition in the subclusters with a high level of confidence, just as they did with the real data.

We would expect that, in principle at least, increasing the number of redshifts in our sample would boost our chances of detecting evidence of differences between the giants and

dwarfs. However, there are only so many galaxies there to be measured. We estimate that roughly 670 of the dwarf galaxies listed in the GMP catalogue, which is complete to $b = 20$, are actually cluster members. The reasoning behind this is that about 52% of the galaxies with measured redshifts (and bluer than the top edge of the cluster colour-magnitude relation) are actually cluster members, so roughly the same percentage of the total number of dwarfs in the GMP catalogue (again, bluer than the top edge of the cluster colour-magnitude relation) are likely to be cluster members. If we had redshifts for all 670 of these dwarfs, would we then be able to detect significant differences between the giants and the dwarfs? To answer this question, we ran a final set of merger-mimicking simulations, this time including all the giants and 670 dwarfs, drawn at random from the catalogue. The chances of detecting differences did improve slightly with the increased sample size, but still not enough to be statistically significant. The 2D K-S two-sample test found on average that there was a 87% chance that the giant and dwarf D-vs-cz distributions were different; only 5% of the simulated distributions were found to have a >99% chance of being different. This suggests that even if we measured redshifts for every dwarf in the cluster brighter than $b = 20$, we would still not have a high chance of detecting evidence of equipartitioned subclusters in the D-vs-cz distributions.

Even though this toy model of a merger scenario is contrived, it demonstrates that Coma *could* indeed consist of equipartitioned subclusters. Indeed, the subcluster equipartitioning seems to generate the sort of non-Gaussianity in the giants (but not the dwarfs) that we see in the real data. However, it doesn't generate differences between the giant and dwarf distributions that are strong enough to detect with our direct statistical comparisons, even if we measured the redshifts of all dwarf cluster members down to $b = 20$.

5. Conclusion

The distribution of line-of-sight velocities for giant galaxies (those with $b < 18$) in the Coma cluster shows strong evidence of non-Gaussianity, caused primarily by a large gap in velocities around $cz = 6500$ km s^{-1}. This gap, and others in the distribution, seem to correspond to the velocities of the cD galaxies NGC 4489 and NGC 4839, but it is still a mystery whether or not the cD galaxies are directly responsible for causing the gaps. Unlike that for the giants, the distribution of velocities for a sample of dwarf galaxies ($b > 18$) exhibits no significant non-Gaussianity and no significant gaps. However, tests directly comparing the localised velocity substructure and spatial substructure in the giant and dwarf distributions show no strong evidence for significant differences between the two populations. Our results rule out the cluster as a whole having moved significantly towards equipartition.

On the other hand, they are consistent with the possibility that Coma formed from the merger of subclusters that were in equipartition; indeed, our simulations suggest that such a scenario can explain the non-Gaussianity of the giant line-of-sight velocity distribution and the contrasting Gaussianity of the dwarfs. We also find that such a merger scenario may not generate a strong enough difference between the giant and dwarf distributions to be able to detect by direct statistical comparison, even if the redshifts of all cluster members brighter than $b = 20$ were measured, so more sensitive tests must be developed to put stronger constraints on Coma's merger history.

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TABLE 1

RESULTS FOR D-VS-cz

Range	χ^2	K-S	Monte-Carlo
Large range	81%	71%	81%
Central range	15%	85%	28%

TABLE 2

RESULTS FOR VELOCITY SLICES

Range	χ^2	K-S	Monte-Carlo
A ($5400<cz<6600$ km s^{-1})	64%	17%	36%
B ($6400<cz<7600$ km s^{-1})	22%	19%	10%
C ($7400<cz<8600$ km s^{-1})	27%	84%	24%

TABLE 3

RESULTS FOR PROJECTED POSITION ON THE SKY

Range	χ^2	K-S	Monte-Carlo
Large range	71%	92%	83%
Central range	59%	35%	86%
Around NGC 4839	57%	55%	34%
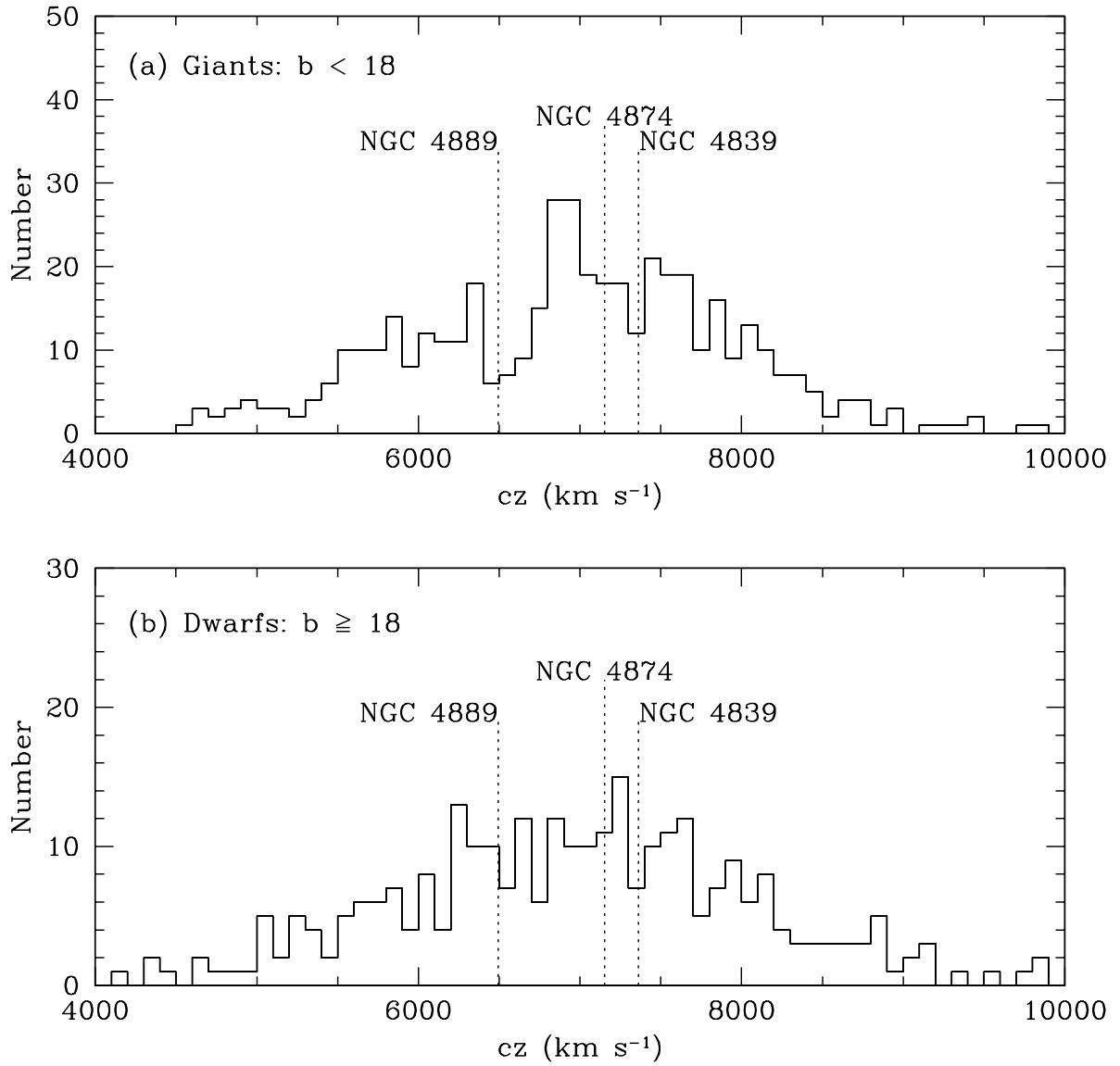
Fig. 1.— Histograms of the line-of-of sight velocity distribution for galaxies in the Coma cluster. (a) Giants (b < 18). (b) Dwarfs (b > 18).
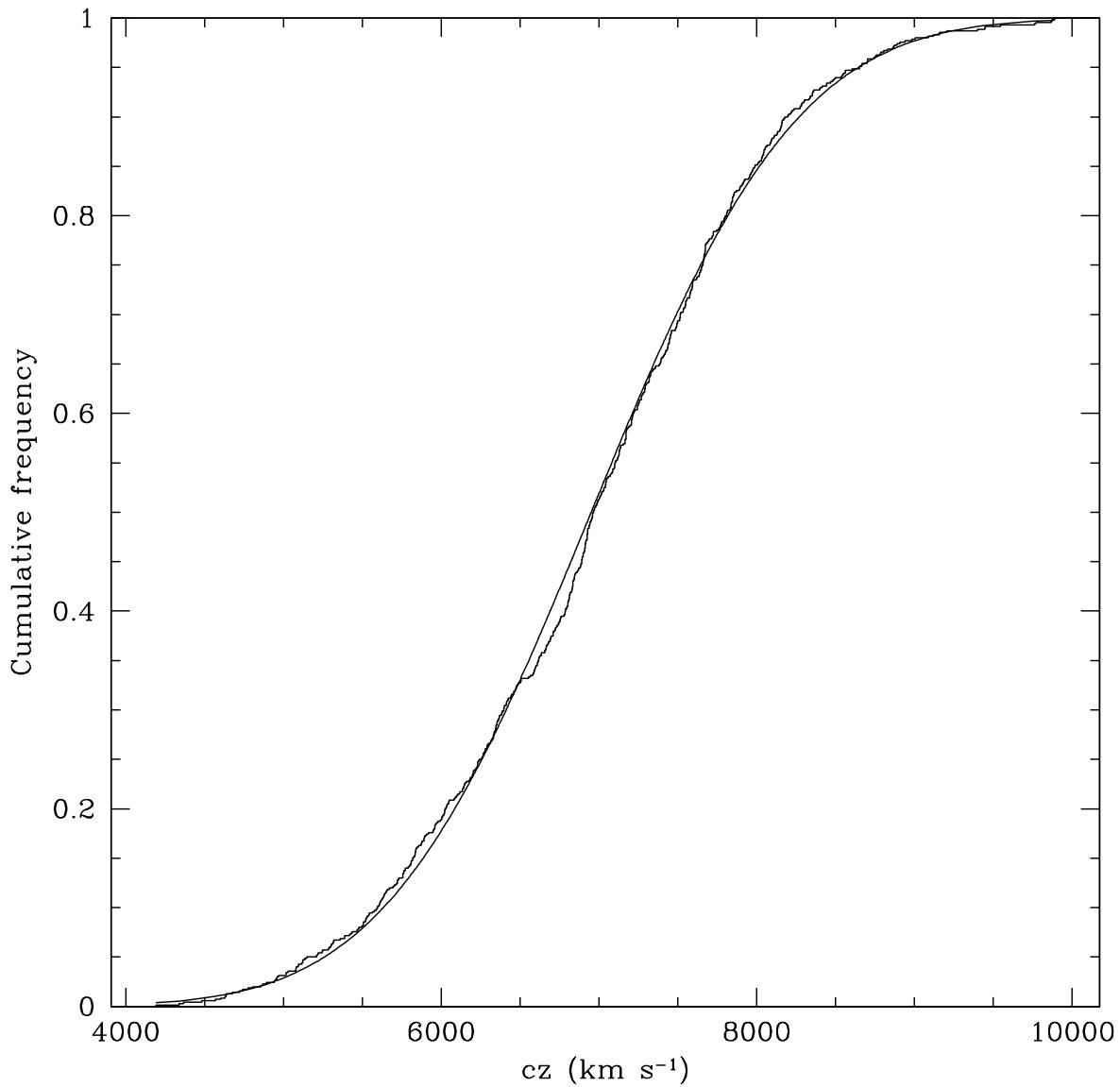
Fig. 2.— Cumulative frequency of giants as a function of redshift (stepped line) superimposed on a cumulative Gaussian (smooth curve) that has the same mean and dispersion as the giants. Note that the largest gap between the two, which defines the K-S statistic, is at cz ~ 6500 km s^{-1}.
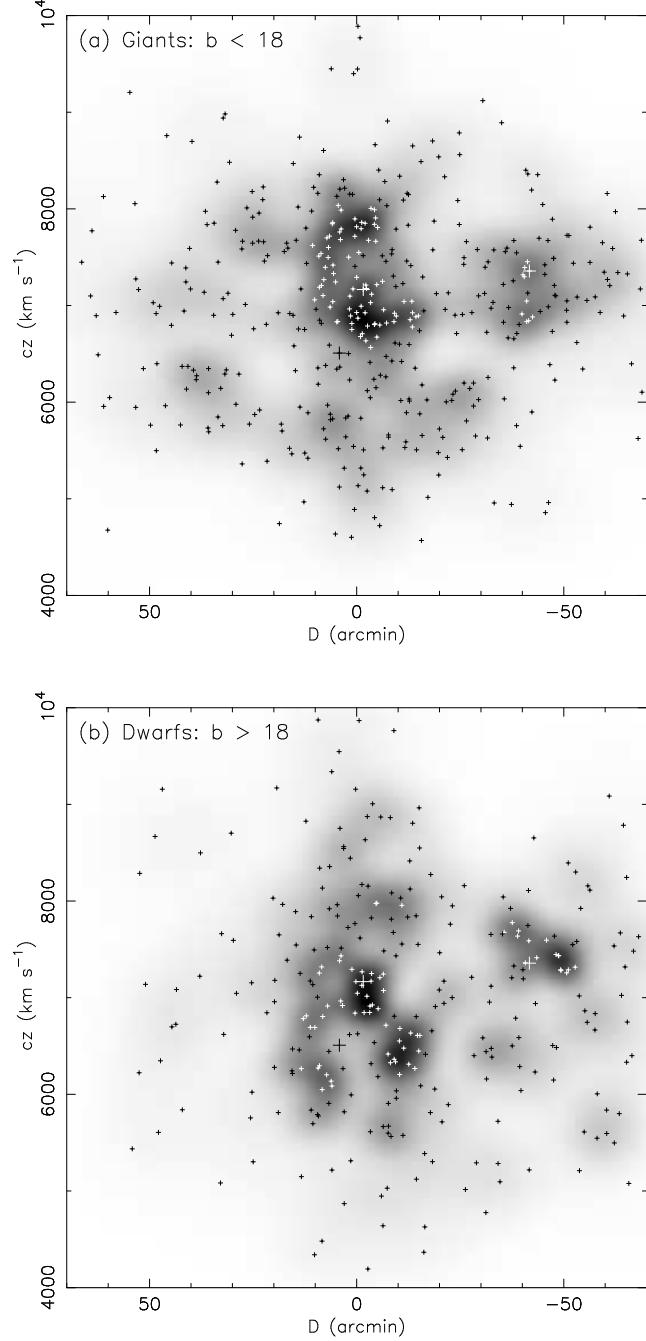
Fig. 3.— Smoothed density of galaxies as a function of line-of-sight velocity cz and distance D along the NE-SW axis of the cluster (where NE is positive). (a) is the distribution of giants, and (b) is the distribution of dwarfs. In each case the density is smoothed using an adaptive 2D Gaussian kernel with base dispersions $\sigma_D = 5'$ and $\sigma_{cz} = 200$ km s^{-1}. The small crosses mark the positions of the galaxies; the three large crosses represent the three dominant galaxies: from left to right, NGC 4889, NGC 4874 and NGC 4839.
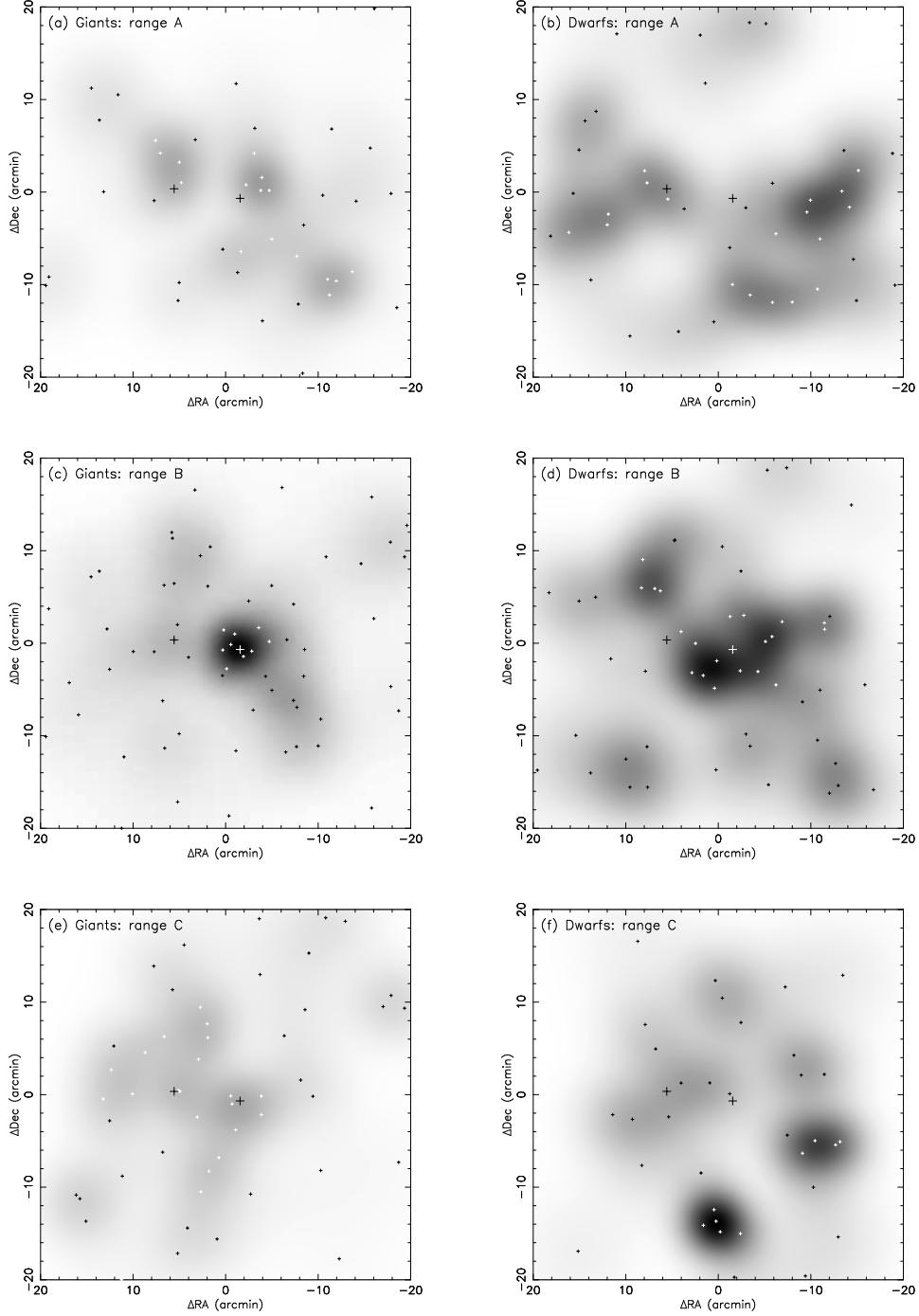
Fig. 4.— Six slices in velocity through the ΔRA-ΔDec-cz distribution: (a), (c) and (e) are the distribution of giants in the velocity ranges A, B and C respectively; (b), (d) and (f) are the same but for the dwarfs. The three ranges are A: $(5400 < cz < 6600)$, B: $(6400 < cz < 7600)$, and C: $(7400 < cz < 8600)$, where cz is in km s^{-1}. Each density plot was smoothed with an adaptive 2D Gaussian kernel with base dispersions $\sigma_{\Delta\text{RA}} = \sigma_{\Delta\text{Dec}} = 3'$. The small crosses are the positions of the galaxies, and the two large crosses are NGC 4889 (left) and NGC 4874 (right).
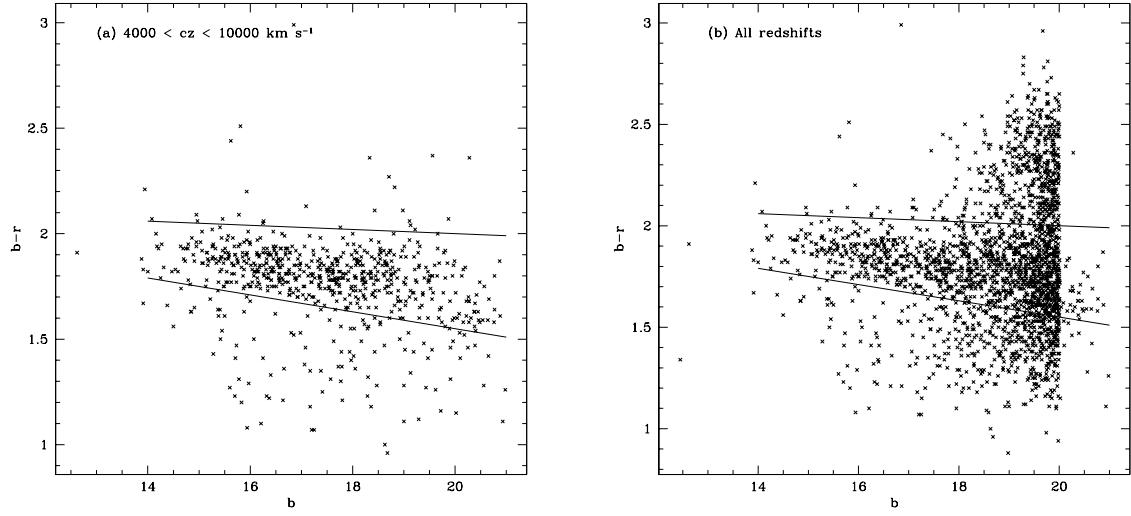
Fig. 5.— (a) b-r colour plotted against magnitude b for all galaxies within the redshift range $(4000 < cz < 10000)$ km s^{-1} (and thus deemed to be members of the cluster). The solid lines delineate the band within which most of the points fall. (b) The same plot for all galaxies, regardless of redshift. Any galaxies without measured redshifts, and that fall outside the cluster colour-magnitude relation determined from (a), are assumed to be field galaxies and are neglected.
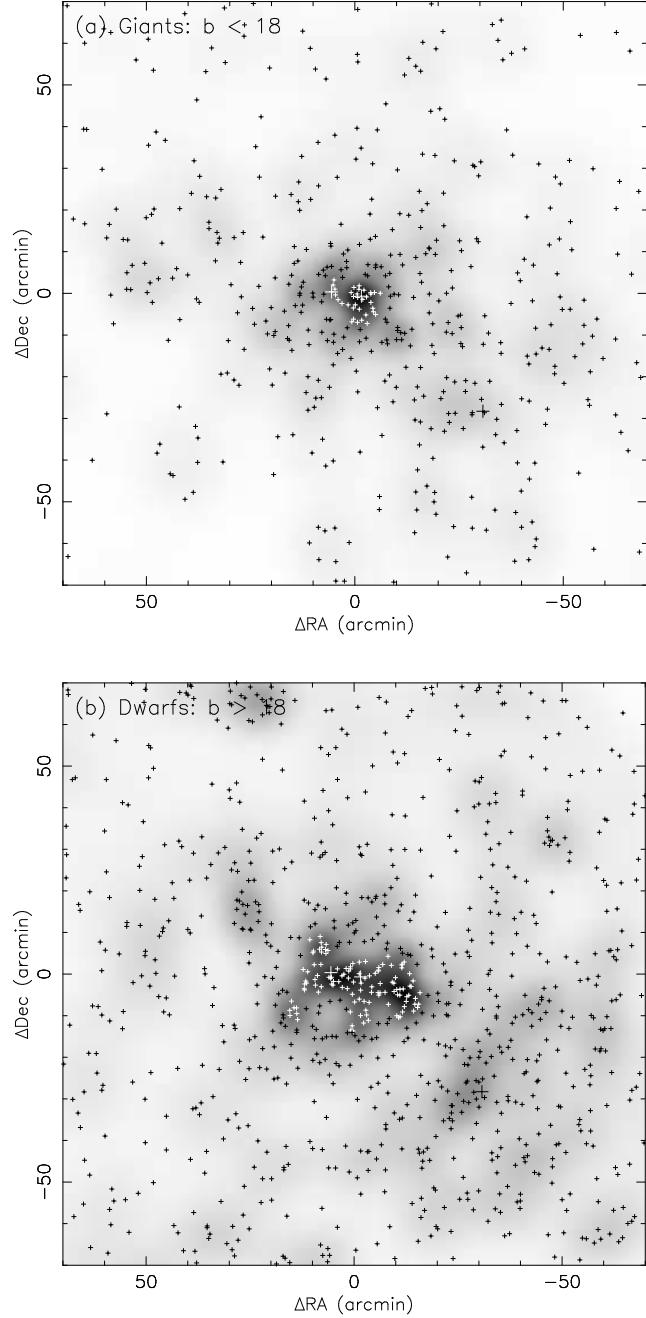
Fig. 6.— Density plots of spatial position for giants (a) and dwarfs (b). The galaxy samples used here include all galaxies with $4000 < cz < 10000$ km s^{-1} plus galaxies without redshifts but within the cluster colour-magnitude relation (see Fig. 5). Smoothing is done with an adaptive 2D Gaussian kernel with base dispersions $\sigma_{\Delta RA} = \sigma_{\Delta Dec} = 5'$. As before, the small crosses mark the positions of the galaxies and the large crosses mark NGC 4889, NGC 4874 and NGC 4839 (from left to right).